Potential for airborne offbeam lidar measurements of snow and sea ice thickness

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Abstract

This paper discusses the capabilities and limitations of a new approach to airborne measurements of snow and sea ice thickness. Such measurements can help better understand snow and sea ice processes, and can also contribute to the validation of satellite measurements. The approach discussed here determines physical snow and sea ice thickness by observing the horizontal spread of lidar pulses: The bright halo observed around an illuminated spot extends farther out in thicker layers, because photons can travel longer without escaping through the bottom. Since earlier studies provided ground-based demonstrations of such sea ice retrievals, this paper presents a theoretical analysis of additional uncertainties that arise in airborne observations of snow and sea ice. Snow and sea ice retrievals pose somewhat different challenges because while sea ice is usually much thicker, snow contains a much higher concentration of scatterers. As a result, sea ice halos are larger but snow halos are brighter. The results indicate that airborne sea ice retrievals are possible at night and that snow retrievals are possible during both night and day. For snow thicknesses less than about 50 cm, observational issues such as calibration uncertainty can cause retrieval uncertainties on the order of 10% in 1 km-resolution retrievals. For moderate snow and sea ice thicknesses (<30 cm and 3 m, respectively), these issues cause similar (~10%) uncertainties in sea ice thickness retrievals as well. These results indicate that offbeam lidars have the potential to become an important component of future snow and sea ice observing systems.

1. Introduction

Snow and sea ice thicknesses are not only indicators of the growth and melt of snow cover and sea ice, but they also influence surface fluxes of heat, radiation, and momentum. Yet, snow and sea ice thicknesses are among the least known parameters of the cryosphere. The pressing need for large-scale measurements of these parameters spurred the development of a variety of remote sensing methods. For example, sea ice thickness is often estimated using freeboard altimetry based on lidar or radar observations (e.g., Comiso et al., 1991; Wadhams et al., 1991; Laxon et al., 2003) or using ice classification based on synthetic aperture radar (SAR) data (e.g., Steffen and Heinrichs, 2001; Kwok and Cunningham 2002), whereas snow thickness is often estimated from passive microwave observations (e.g., Markus and Cavalieri 1998; Kelly et al. 2003). These measurements provided numerous important insights but remain affected by substantial uncertainties. For example, freeboard sea-ice measurements suffer from the lack of direct information on snow thickness and from uncertainties in sea level and instrument altitude, whereas microwave snow measurements are affected by calibration uncertainties and surface roughness (e.g., Kwok et al. 2004; Powell et al., 2006; Stroeve et al. 2006). This paper examines the feasibility of a new approach that uses offbeam lidar data for simultaneous measurements of snow and sea ice thickness.

As illustrated in Figure 1, offbeam lidars detect diffuse return signals from several annular rings. These instruments determine the thickness of highly opaque media by observing the horizontal spread of lidar pulses: The bright halo observed around the illuminated spot extends farther out in thicker layers, because photons can travel farther without escaping through the bottom (e.g., Voss and Schoonmaker 1992; Davis et al. 1997, 2002) (Figure 2). This measurement approach was used in several disciplines, providing thickness measurements for media as diverse as tooth enamel and thick clouds (e.g., Groenhius et al. 1983; Cahalan et al. 2005a; Polonsky et al. 2005). Moreover, results from ground-based experiments in Table 1 of Haines et al. (1997) suggest to us that this approach can provide accurate thickness measurements for sea ice as well. (In these ground-based experiments ice thickness and extinction coefficient were obtained using data from a light detector that moved around a lamp illuminating the ice at a single point.) This paper examines whether the approach can be used for *airborne* measurements of snow and sea ice thickness.

Our focus is on the THOR (Thickness from Offbeam Returns) instrument, which was able to measure the thickness of highly opaque clouds up to 1000 m thick with an uncertainty less than 50 m (Cahalan et al. 2005a). A slightly modified version of THOR (referred to as THOR4Ice) was flown on board the NASA P-3 aircraft during the 2003 AASI (Antarctic AMSR-E Sea Ice) experiment over the Bellingshausen Sea—a region that has been the subject of numerous studies examing a wide range of topics such as long-term changes in sea ice cover, thickness and roughness of sea ice and snow, and processes of ice growth through flooding or refreezing of melted snow (e.g., Jeffries et al. 1997; Adolphs 1998, 1999; Haas et al. 2001, Parkinson 2002). The flights in 2003 allowed us to test instrument performance and refine observational procedures (for example, the adjustment of filter levels for strong, yet unsaturated signals over highly reflective and variable surfaces). This study presents a theoretical analysis of expected offbeam lidar capabilities and limitations in measuring snow and sea ice thickness. Since the accuracy of the retrieval approach was already demonstrated using in-situ observations of sea ice (Haines et al. 1997), we focus on exploring issues specific to airborne observations: Namely whether airborne lidars can provide observations at a sufficiently high quality for thickness retrievals, and whether horizontal variability over the measurement area or atmospheric scattering cause significant uncertainties. We also explore whether snow retrievals are affected by uncertainties not applicable to sea ice retrievals. This analysis provides insights into the potential merits of a novel retrieval approach and also provides guidelines for developing offbeam lidars for snow and sea ice observations.

Finally, we mention that even though this paper focuses on retrievals of geometric thickness, offbeam lidars also provide information on snow and ice extinction coefficients (Figure 2). In ground-based measurements, the diffusion of light emitted by a point source has already been used for estimating sea ice microphysical properties (e.g., Trodahl et al. 1987; Maffione and Jaffe 1995; Haines et al. 1997). Moreover, numerous studies (e.g., Grenfell and Maykut 1977) indicated that the extinction coefficient of snow is closely related to its microphysical properties (e.g., age, density, and grain size), which raises the possibility of microphysical retrievals using offbeam lidars.

The outline of the paper is as follows. Section 2 describes our theoretical simulations of offbeam lidar data, then Section 3 describes the methodology of hypothetical snow and sea ice thickness retrievals. Sections 4 and 5 then discuss the accuracy that can be expected from airborne measurements of snow and sea ice thickness, respectively. Finally, Section 6 presents a brief overview and a few concluding remarks.

2. Simulation technique

We simulate offbeam lidar data using a three-dimensional Monte Carlo radiative transfer model. Earlier versions of this model have been verified in the I3RC (Intercomparison of 3D radiative Codes) project and have been used successfully in the analysis of THOR cloud observations (Cahalan et al. 2005a, b). For this study, the model was modified to include absorption by aerosols, bulk ice, and algae, to consider refraction at ice boundaries, and to allow for vertical anisotropy in sea ice scattering coefficient. We note that photon pathlengths are often shorter in horizontal than vertical directions because scatterers such as air bubbles and brine pockets often form vertical channels or tubes—both because wind, currents, and thermal expansion can create horizontal pressures in the ice, and because small brine pockets tend to merge into long tubes mainly along the sides of small ice platelets, which tend to be oriented vertically because of the preferred direction for ice crystal growth. (e.g., Weeks and Ackley 1982; Cole and Shapiro 1998; Light et al. 2003).) We perform the simulations for THOR's wavelength, 540 nm. In order to ensure low uncertainties in our results, we typically simulate $5*10^7$ to $2*10^9$ photons. Higher photon numbers are computationally feasible for less opaque situations such as thin or wet snow. The random noise in Monte Carlo results was kept at suitable levels by using several variance-reduction techniques such as the method of local estimates (e.g., Marchuk et al. 1980), in which the higher rate of scatterings for each photon can partially compensate for the lower number of simulated photons in highly opaque situations.

The simulated scenes consist of overlying homogeneous layers, each with different scattering and absorption properties. To consider the wide variability in snow microphysical properties, we follow Wiscombe and Warren (1981a) and consider three widely different snow types: fresh, old, and wet snow. Snow density for the three categories is assumed to be 0.1, 0.2, 0.4 times the density of water. The radiative properties of snow particles are obtained from Mie calculations that assume spherical particles with radii 50 µm, 200 µm, and 1000 µm for the three categories (Wiscombe and Warren 1981a). We note that old dry snow often lies between our "old" and "wet" categories (e.g., Massom et al. 1997, 2001), and so our "old" category may be most representative of moderately aged snow. We also included an even more dense wet snow category that had a density 0.7 times that of water, and a grain radius of 1200 µm. Such dense snow was reported in several studies of snow over Antarctic sea ice (e.g., Massom et al. 1997, 2001). Unless noted otherwise, the calculations include an aerosol content of 4 ppbw, which is in the typical range of recent observations in both the Arctic and the Antarctic (e.g., Grenfell et al. 2002; Hansen and Nazarenko 2004). The aerosol absorption cross section is assumed to be 10 m^2/g (see footnote #3 in Wiscombe and Warren 1981b). Following Haines et al. (1997), we calculate radiative transfer in sea ice using the Delta-isotropic assumption, with direction-dependent scattering coefficients in the range of 3-6 m^{-1}. Ice absorption coefficient is set to 0.07 m^{-1} (Grenfell and Perovich 1981).

The results of Monte Carlo simulations are aggregated to radial- and range-resolutions representative of expected airborne observations. While the size of annular fields-of-view (FOVs) vary with aircraft altitude in actual experiments, we use fixed fields-of-view with outer radii of 5, 10, 20, 40, 80, 160, 320, and 640 cm. Similarly to THOR cloud observations, the fields-of-view get increasingly wide in order to maintain high signal levels even in the outer, fainter regions of the diffuse halo. Our calculations use the range-resolution of the current instrument, 30.8 m. We note, however, that using a higher range-resolution (some lidars use 15 cm or less) could improve retrieval accuracies by reducing observational noise and by providing additional information on surface roughness and freeboard.

3. Retrieval methodology

Our retrieval algorithm is limited by two main considerations. First, we use only the relative calibration of multiple FOVs. This is important not only because it would be difficult to maintain accurate in-flight absolute calibration, but also because variations in atmospheric and snow attenuation could confuse retrievals that rely on absolute calibration. Second, we don't use the central FOV, because its signal is dominated by direct backscatter from the snow surface and so is highly sensitive to variations in microphysical snow properties (such as a thin crust of ice at the snow surface). Fortunately, multiple scattering greatly reduces this sensitivity for outer views, which are influenced predominantly by geometrical thickness, volume scattering coefficient, and absorption properties. We emphasize, however, that central FOV observations would still be important for detecting the influence of atmospheric aerosol and cloud scattering in our measurements. In case of high range-resolution, the central FOV could also help characterize surface roughness and large-scale horizontal variability, and could even measure sea ice freeboard—thus helping in situations where halo-based retrievals have large uncertainties (e.g., thick snow over thick ice).

Our test retrievals work by selecting the snow and ice properties that minimize the difference between observations and pre-calculated look-up tables. (We note that in this study, look-up tables and simulated observations were both generated using the Monte Carlo model described in Section 2.) Relying on the widely used approach of weighting observations according to their uncertainty (giving more weight to more reliable data), we quantify the difference (D) between observations and look-up tables using the equation

$$D = \frac{1}{\sum_{i=2}^{N_{FOV}} \sigma_i} \sum_{i=2}^{N_{FOV}} \sigma_i \frac{R_i^{obs} - R_i^{LUT}}{R_i^{obs}} \quad (1)$$

where N_{FOV} is the number of FOVs, σ_{i} is the signal-to-noise ratio estimated for the i^{th} FOV, and the ratios R_{i} describe what percentage of the overall photon count (C) is detected at the i^{th} FOV:

$$R_i = \frac{C_i}{\sum_{j=2}^{N_{FOV}} C_j}. \quad (2)$$

4. Snow retrieval uncertainties

This section discusses snow thickness retrieval uncertainties related to instrument performance, such as observational noise, calibration errors, and laser beam spreading, and also related to scene characteristics such as spatial variability, presence of clouds and aerosol, and underlying surface.

4.1 Instrument performance

We estimate retrieval uncertainties for instrument capabilities similar to those of the existing THOR4Ice system, but allowing for a few low-cost upgrades that we intend to implement using commercially available components (Table 1). By enabling more narrow spectral filters, laser beam, and telescope views, these relatively minor upgrades will allow retrievals from higher altitudes and at a higher spatial resolutions, even for thinner snow and sea ice. Flight characteristics were chosen by considering P-3 aircraft capabilities: 300 knots (~150 m/s) flight speed at 8 km flight altitude.

Observational noise

The observational noise of the THOR instrument is dominated by the so-called "photon shot noise", which arises from the random nature of individual photon arrivals at the lidar detector (Cahalan et al. 2005a). We simulate this noise using the method that proved successful for simulating THOR observational noise in Cahalan et al. (2005a): We first estimate the signal-to-noise ratio values and then add a corresponding amount of Gaussian white noise to the supposedly perfect Monte Carlo simulation results. In order to get an overall picture of noise effects, we repeat our test retrievals 100 times, each time for a random noise generated using different random numbers. Thus each result presented below is obtained as the root-mean-square uncertainty of 100 retrievals.

Finally, our tests consider that actual observations may need neutral density filters to avoid saturating the photon counting detectors. We assume that—following the procedures tested during the 2003 AASI campaign—filter levels are set for each FOV so that photon counts fall between 16 and 50% of saturation.

Figure 4 indicates that the effect of noise on retrieval uncertainty increases with snow thickness and horizontal resolution. Still, even under the difficult conditions of 30° solar elevation and 8 km flight altitude, noise-related uncertainties for 30 and 50 cm thick old dry snow remain near 3%, as long as the observations are averaged over 300 or 1200 m, respectively. The results also show that the overall bias of retrievals remain insignificant even for high-resolution retrievals, if the results are averaged over sufficiently long segments. This occurs because, as theoretical considerations indicate (e.g., Davis et al, 1997), the size of the bright halo depends linearly on layer thickness—and so if noise makes the halo appear too large in some places and too small in others, the resulting retrieval errors will cancel out each other.

Figure 5 illustrates the resolution-dependence of retrieval uncertainties for current instrument capabilities (including the low-cost improvements mentioned above) and also for an upgraded instrument that would use ~9 times faster (1 GHz) commercially available photon counters and an automated iris mechanism to maintain higher (but still unsaturated) signal levels. These upgrades would allow us to base the retrievals on a higher number of photon counts, thus reducing the "photon shot" noise that is caused by the random nature of individual photon arrivals. Although Figure 5 does not include this option, horizontal resolution could be further increased by switching to a laser with faster pulse rate. For example, incorporating the laser of the widely used MicroPulse Lidars (MPL) would allow increasing the horizontal resolution by a factor of 2.5. However, this additional gain in snow retrievals should be balanced against a loss of resolution in sea ice retrievals, whose main limitation is not pulse rate, but overall laser energy—which is 55% lower in MPL than in THOR4Ice.

Figure 6 shows that noise has smaller effects at night, because the lidar signal is less affected by the more than 5 orders of magnitude weaker lunar illumination than by sunlight. In fact, our simulations indicate that most of THOR's nighttime noise arises not from background illumination but from the random arrival of laser-emitted photons—which implies that nighttime uncertainties could be best reduced not by using narrower spectral filters but by faster photon detectors that could count a larger, statistically more reliable number of photons without reaching saturation.

Figure 6 also highlights the importance of snow conditions on measurement accuracy: Noise effects are stronger for fresh snow than for aged or even wet snow, which contain much fewer, albeit larger, snow crystals. This is because fewer photons can travel to the base of snow cover and then return to the detector in highly scattering fresh snow than in less opaque old or wet snow. Although the concentration of scatterers may change somewhat when snow gets saturated or melts and refreezes, the intensity of light scattering remains much below that for fresh snow—and so we expect uncertainties for saturated, refrozen snow to remain close to those for old and wet snow. If confirmed by field experiments, this behavior will be in contrast with that of radar and passive microwave measurements, whose accuracy in such situations can be affected by differences between the dielectric properties of snow and water or ice.

Finally, we note that noise effects could not be reduced substantially by flying at lower altitudes, because the gain in signal strength would be largely offset by the need for stronger neutral density filters to avoid detector saturation. Still, lower flight altitudes would help the retrievals for other reasons such as narrower laser beam, higher radial resolution, and less complications due to clouds or atmospheric aerosol.

Calibration

We examine the effects of calibration uncertainties by perturbing the simulated photon counts by a different random factor for each FOV, and by analyzing the way retrieval uncertainty changes with the average magnitude of perturbations. Again, we obtain a statistical description of uncertainties by performing groups of 100 retrievals, each using a different set of random numbers. Figure 7 shows that the effects of 4% uncertainty in relative calibration are comparable to the effects of observational noise in 1.2 km-resolution daytime observations. However, we expect that the calibration procedures described in Cahalan et al. (2005a) will allow us to maintain a relative calibration at better than 4% accuracy. These procedures involve a combination of laboratory experiments (using integration spheres and other equipment), pre-flight and post-flight tests (using homogeneous diffuser disks), and continuous in-flight monitoring of background illumination signal (considering that after appropriate time-averaging, background reflectances should be statistically similar in all FOVs). As a result, we do not expect relative calibration to be a major obstacle to accurate snow thickness measurements, except for very thick snow.

Finite beam effects

While the calculations above assume an ideal point beam laser source, actual laser beams have a finite width. Figure 8 shows that a moderate, realistic widening of the beam (radius < 9 cm) does not pose significant problems as long as the beam is well characterized. Further widening causes retrieval problems for thin snow first, because it blurs the small halos that form in thin snow. As the beam widens further, retrievals over thick snow get affected as well.

We found that accurate knowledge of beam width is just as important as keeping the beam width low. For example, if the real beam is wider than assumed, retrievals will attribute the resulting extra wide return signal to a larger halo and will overestimate snow thickness. Even fairly small errors in beam width (e.g., 6 cm instead of 3 cm at the $1/e^2$ level) can affect retrievals even for thick snow: Extra widening of a typical, Gaussian-shaped laser beam implies that more photons will reach the snow at the tails of the Gaussian distribution and will enhance the weak signal of outer FOVs. Still, we expect to provide beam characteristics at sufficient accuracy using a combination of laboratory tests and in-flight monitoring of lidar returns from surfaces that do not create diffuse halos, such as asphalt, rocks, or sand.

4.2 Scene properties

Atmospheric scattering

In principle, scattering by clouds or atmospheric aerosol can widen the incoming laser beam and cause overestimations of snow thickness. However, the results in Figure 9 indicate that this is not a serious problem for thin layers (e.g., $\tau < 0.2$): Unless the cloud or aerosol is at very low altitudes (a few hundred meters), most of the scattered photons reach the surface so far out to the side that they don't influence our retrievals. Thicker clouds and aerosol, however, can weaken the unscattered laser beam and thus reduce signal levels and signal-to-noise ratios. As a result, thick clouds and aerosol can reduce retrieval resolution or prevent snow retrievals altogether—which implies that we need to monitor atmospheric conditions using the central FOV.

Variations in snow properties

Variations in snow properties can also influence retrieval accuracy. Halo-based retrievals can minimize this influence by not using the central FOV: multiple scattering largely washes out the influence of crystal shape and size by the time photons reach the outer FOVs (e.g., Voss and Schoonmaker 1992; Xie et al. 2006). Haines et al. (1997) demonstrated that halo-based retrievals can provide sea ice properties (thickness and rescaled extinction coefficient) for multiple overlying layers as long as the retrievals can use at least two FOVs relevant to each layer. Our results (not shown) indicate that this is largely true even for snow retrievals: For example, even though 10 cm of highly scattering fresh snow on top weakens the signal from an underlying older snow layer, this weakening does not cause drastic reductions in retrieval accuracy. As for horizontal variability, we found that retrieval uncertainties reach about 10% of thickness variability in the worst case (where exactly half of the retrieval area is covered by uniformly thin and thick snow, respectively). This implies that horizontal variability effects are negligible in smoother regions but may reach 1-2 cm in rough areas where snow thickness was observed to vary by 20-40 cm (e.g., Warren et al 1999; Herzfeld et al. 2006). In highly variable areas, however, where snow thickness can vary by a meter or more within a distance of a few meters, retrievals are expected to have much larger uncertainties. We note that, detectors with high range-resolution (e.g., 15 cm) could help characterize surface roughness and consider its effects in halo-based retrievals, or at least flag the retrieval results as less reliable in rough areas.

Variations in the aerosol content of snow can also influence retrievals: Absorbing aerosol can reduce the number of photons that reach the outer FOVs, and retrievals may misinterpret the resulting smaller halos as a sign of thin snow (as if the absorbed photons had escaped through the base of the snow layer). Our calculations discussed so far assume a 4 ppbw concentration for carbonaceous absorbing aerosol (soot), which is in the typical range of recent observations in the Arctic and Antarctica (e.g., Grenfell et al. 2002; Hansen and Nazarenko 2004). The calculations assume 10 m^2/g absorption cross section, which can be considered representative of soot particles (Wiscombe and Warren 1981b). Figure 10 shows that if our retrievals don't consider changes in absorbing aerosol content, significant retrieval uncertainties can arise in polluted areas where concentrations can reach beyond 30 ppbw. (We note that even background levels used to reach 30 ppbw a few decades ago, when Russia and other countries emitted more pollutants (e.g., Clarke and Noone 1985).) This result implies that stand-alone halo-based snow retrievals should be limited to relatively clean areas. We emphasize, however, that halo-based snow retrievals will work even in more polluted areas if aerosol effects can be estimated either from surface observations or, following the approach in Warren (1982), from coinciding observations by a multispectral radiometer. We note that radiometers could help even in the presence of vertical variations in aerosol concentration: If vertical variations enhance aerosol effects in radiometer observations, they do the same in lidar returns as well.

Finally, we mention that for snow over land, variations in surface albedo have little effect on our retrievals, because ground albedo is comparable to that of a very thin snow layer. As a result, surface variations are expected to cause retrieval errors of only a few mm at most.

Overall

We can obtain combined uncertainty estimates by assuming that the individual uncertainties discussed above act independently from one another. Using realistic estimates for each source of uncertainty—variations in snow aerosol content (~7%), observational noise (~6%), uncertainties in laser beam width (5%), horizontal snow variability (~3%), and calibration uncertainty (~2%)—suggest a combined uncertainty near 10% for snow thicknesses less than 50 cm and horizontal resolutions near 1 km. These estimates do not include uncertainties due to variations in snow layer and snow crystal structure, which we intend to examine using actual (ground-based) observations. However, because the retrievals don't use the central FOV that is most sensitive to snow microphysics, and because halo-based retrievals seemed to work well for multilayer sea ice structures (Haines et al. 1997), we expect that that the additional uncertainties will not increase drastically the ones discussed in this paper.

5. Sea ice retrieval uncertainties

This section discusses sources of uncertainty in sea ice thickness retrievals, focusing on issues that are most different both from snow retrievals and from the in-situ sea ice retrievals discussed in Haines et al. (1997).

Retrieval conditions are markedly different for sea ice and snow partly because sea ice tends to be much thicker, but also because it contains a much smaller concentration of scatterers (e.g., air bubbles and brine pockets) than the typical concentration of snow crystals. As a result, return signals from sea ice are spread over a much wider area (several meters in radius) and are much weaker, especially if the ice is blanketed by snow (Figure 2). These factors result in ice retrievals being much more sensitive than snow retrievals to observational noise and calibration uncertainty even at night (Figure 11). As expected, the figure shows that uncertainties increase with both snow and ice thickness and with calibration uncertainty. Even so, retrieval uncertainties remain below 10% for moderate (< 3 m) sea ice thicknesses at realistic resolutions and calibration errors.

Figure 12 illustrates the resolution-dependence of uncertainties in nighttime sea ice thickness retrievals. The figure reveals that for 2 m thick ice, observational noise and expected calibration errors cause less than 10 % retrieval uncertainty even at full (~77 m) resolution. The upper scale at the figure suggests that after some upgrades (doubling the telescope size and extracting time-averaged data at a higher resolution than the current 0.5 s), such accuracy could be achieved at resolutions of only a few tens of meters. Such high resolutions could allow useful retrievals around leads or even in broken ice fields, and could reduce any uncertainties arising from horizontal variability.

In contrast to the encouraging nighttime results, Figure 13 shows that daytime observations are highly sensitive to calibration uncertainties. This is because the combination of much larger (~100X) FOVs and much weaker signals in ice than snow allows background solar illumination to dominate over the ice signal in outer FOVs—and so even a small percentage error in the overall photon count implies a large relative error in the photon count attributed to the laser signal. This problem can be alleviated once suitable ultra-narrow spectral filters (now under development) become available. Until then, the sensitivity to measurement errors limits sea ice retrievals to nighttime.

Finally, horizontal variability also causes somewhat larger uncertainties in sea ice than in snow retrievals: In worse-case scenarios (where each half of the measurement area is covered by ice of different thickness) the retrieval error can reach 20% of the thickness difference between thicker and thinner areas. This implies that if ice thickness increased gradually from 2 m at one end of a measurement area to 3 m at the other end, the unresolved variability would cause a 10 cm (~4%) error in the retrieved average ice thickness (2.4 m instead of 2.5 m)—though the effects may be stronger in rough areas such as the ice floes in Perovich (1990). These uncertainties may be reduced if horizontal resolution is increased (e.g., using a larger telescope), or if high-resolution altimetry measurements using the central FOV provided information about small-scale variability at least at the top surface.

Overall, the results suggest that factors specific to airborne observations (noise, calibration, horizontal variability) cause combined retrieval uncertainties in the order of 10% for nighttime moderate resolution (~1 km) retrievals at moderate snow and sea ice thicknesses (less than 30 cm and 3 m, respectively). Since variations in microphysical properties (such as the appearance of algae near the ice bottom) caused much smaller uncertainties in in-situ demonstrations than the uncertainties we estimated for airborne observations (Haines et al. 1997), we expect the overall uncertainty of airborne retrievals to be not too far from the values discussed here.

6. Summary and conclusions

This paper discusses the capabilities and limitations of a new approach to airborne measurements of snow and sea ice thickness. Such measurements are important for better understanding the growth and melting of snow and sea ice, as well as for characterizing surface fluxes of heat, radiation and momentum. Moreover, such measurements would be especially suitable for contributing to the validation of satellite measurements, because they rely on a completely different approach than current snow and sea ice retrievals—and so they are not subject to the same limitations and uncertainties.

The approach discussed here uses offbeam lidar measurements to detect diffuse return signals from several annular rings that are centered on a point illuminated by a laser beam. In this approach, thickness is determined by observing the horizontal spread of lidar pulses: The bright halo observed around the illuminated spot extends farther out in thicker layers, because photons can travel longer without escaping through the bottom. The results of ground-based experiments (Table 1 in Haines et al. 1997) suggest to us that observations of diffuse halos can indeed be used to estimate sea ice thickness. This paper builds on the earlier studies and examines whether the approach could be extended to snow thickness measurements, and whether airborne observations could provide observations at a high enough quality for realizing the potential revealed in ground-based experiments. This analysis can help evaluate the capabilities and limitations of the new approach and can also provide guidelines for future instrument development. Our main findings are as follows:

<u>Snow retrievals</u>

- Both nighttime and daytime measurements are possible.
- At moderate horizontal resolutions (~1 km), retrieval uncertainties discussed here remain near 10% for snow thicknesses less than 50 cm. This estimate considers variations in snow aerosol content, observational noise, uncertainties in laser beam width, horizontal snow variability, and calibration uncertainty.
- Retrieval accuracy is higher for thinner and older snow, whereas uncertainties increase for thicker and more fresh snow.
- Snow thickness retrievals require accurate characterization of the tightly focused laser beam and of the telescope FOVs, and also need an accurate relative calibration of these FOVs. We believe that, using the procedures mentioned in the paper, these technological requirements can be met readily.
- Similar levels of accuracy could be achieved at significantly (10-20X) higher resolutions by upgrading the THOR4Ice instrument using commercially available components. The most beneficial upgrades are: faster photon counting and laser pulse rate, and an automated iris mechanism that can ensure optimal signal strength.

The main limitations of future snow retrievals are expected to be:

- While retrievals are not affected much by thin aerosol or cloud layers, they are not possible if thick cloud or aerosol is present below the aircraft. The magnitude of interference depends on the altitude of the scattering layer but, in general, optical thickness must exceed a few tenths of optical thickness to cause significant problems.
- In polluted areas, uncertainties in aerosol absorption inside snow can cause substantial retrieval uncertainties. In such areas independent information on aerosol effects is required for accurate retrievals. Such information may come from coinciding multispectral radiometer observations or from in-situ measurements.
- Because snow and underlying sea ice is distinguished by their markedly different extinction coefficients, this distinction can become ambiguous at temperatures below the eutectic point

(-22°C), where salt crystallizing inside the ice can bring the ice scattering coefficient close to that of snow. Such problematic areas could be identified using thermal infrared measurements of surface brightness temperature. The distinction of snow and sea ice can also be difficult if sea water floods the top of sea ice and melts some snow, which then refreezes into a frozen slush.

Finally, we emphasize that this study does not consider all potential sources of retrieval uncertainty. In particular, we don't examine all potential effects of variations in snow and crystal structure. Although considerations in Sections 3 and 4 suggest that these uncertainties are likely small, they could be best examined through ground-based validation experiments along the lines of earlier experiments (e.g., Haines et al. 1997). We intend to carry out such experiments by enabling the airborne THOR instrument to take observations from the close ranges involved in ground-based experiments.

<u>Ice retrievals</u>

Our theoretical analysis focuses on issues specific to airborne remote sensing. The main findings are:

- Nighttime sea ice retrievals are feasible.
- At moderate resolutions (~ 1 km), observational noise and calibration uncertainty cause retrieval uncertainties near 10% for moderate snow and sea ice thicknesses (around < 30 cm and 3 m, respectively).
- Uncertainties increase with snow and ice thickness.
- Similar accuracy could be achieved at higher horizontal resolution by enhancing signal strength, either by increasing telescope size or laser power, or by decreasing flight altitude from the 8 km considered here.

The main limitations of future sea ice retrievals are expected to be:

- Daytime retrievals require an ultra-narrow (~0.01 nm) filtering not available on the current instrument. Without such filtering, the main problem is the strong sensitivity of daytime retrievals to even minor calibration uncertainties. As a result, halo-based sea ice retrievals are limited to nighttime until a suitable ultra-narrow filter becomes available.
- Similarly to snow retrievals, ice retrievals are also affected by clouds and atmospheric aerosol, and by salt crystals forming inside the ice at very cold temperatures.

We note that the uncertainties discussed in this paper arise in addition to the uncertainties due to microphysics variations, such as the anisotropy of brine tubes or the thickness of algal growth near the ice base. However, since the results of field experiments by Haines et al. (1997) suggest that those additional uncertainties are smaller than the ones discussed here, we expect that the overall uncertainty of airborne retrievals will be near the values presented in this paper. It is even possible that refinements in our retrieval algorithm or in instrument characteristics will allow lower retrieval uncertainties than those discussed here.

The benefits of offbeam lidars could be enhanced by combining their data with that of other instruments. For example, offbeam lidar measurements could benefit from multispectral radiometer data that could allow accurate retrievals even in polluted areas, from altimetry information that could characterize horizontal variability and provide freeboard estimates even when halo-based retrievals have large uncertainties, from microwave data that could provide constraints on microphysical snow properties, and from thermal infrared data that could indicate if there is a risk of confusing snow and sea ice layers because of the salt crystals that form in the ice at very low temperatures. In turn, offbeam lidar data could provide constraints on geometric thickness and shortwave extinction coefficient, and thus help improve retrieval accuracies for other instruments. For example, offbeam lidars could provide snow thickness and thus alleviate one of the largest sources of uncertainty in freeboard measurements of sea ice thickness (Kwok et al. 2004). Moreover, offbeam lidars also provide information on extinction coefficient, which can help estimating microphysical properties such as snow age, density, and grain size.

Because offbeam lidar retrievals are based on different principles than other snow and sea ice measurement methods, they can help not only in improving our understanding of snow and sea ice processes, but also in validating satellite measurements. Overall, the results indicate that offbeam lidars have the potential to become an important component of future snow and sea ice observing systems.

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Tables

Table 1. Instrument and flight parameters assumed in retrieval tests.

Wavelength	540 nm
Pulse energy	225 μJ
Pulse rate	1 kHz
Pulse duration	8 ns (pulse length ~2.4 m)
Telescope diameter	19.05 cm
Spectral filter bandwidth	1 nm
Overall photon detection efficiency	1/25
Photon counter sampling rate	8.87 ns (~1.33 m range-resolution)
Outer radius of fields-of-view (FOVs)	5, 10, 20, 40, 80, 160, 320, 640 cm
Range-resolution	30.8 m
Flight altitude	8 km
Flight speed	300 knots (150 m/s)

Figures

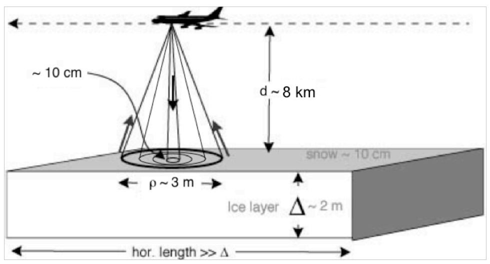

Figure 1. Schematic diagram of airborne sea ice measurements using offbeam lidars.

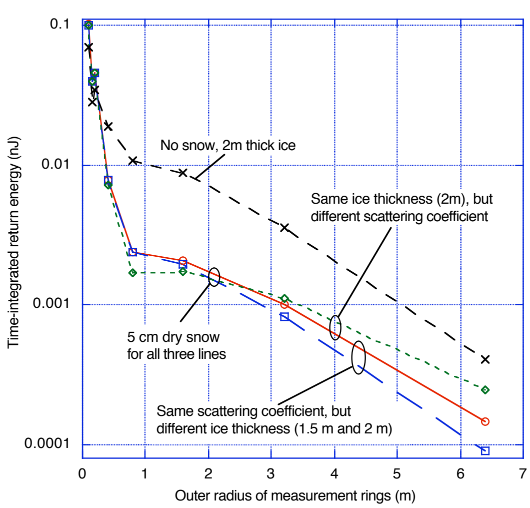

Figure 2. Simulated offbeam lidar signals for various snow and sea ice conditions. The figure was created through 3-D Monte Carlo radiative transfer simulations using the methodology described in Section 3. The figure assumes an instrument roughly similar to THOR flying at 1 km altitude.

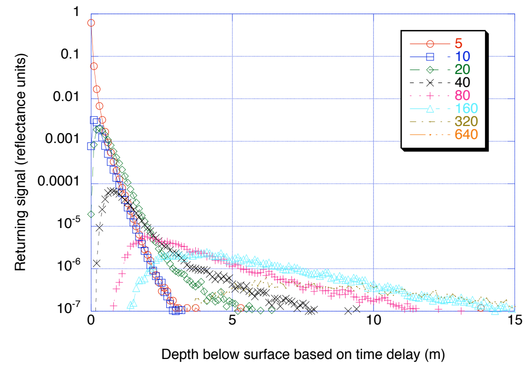

Figure 3. Simulated THOR4Ice data for 2 m thick ice covered by 15 cm snow. The legend indicates the outer radius (in cm) of each annular field-of-view.

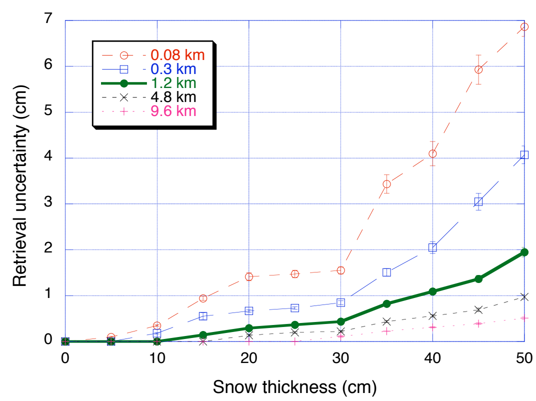

Figure 4. Retrieval uncertainties caused by observational noise. Each curve is for a different horizontal resolution. The calculations are for 30° solar elevation and old snow. The error bars indicate the uncertainty in retrieval uncertainty estimates that arises from the random nature of simulated observational noise.

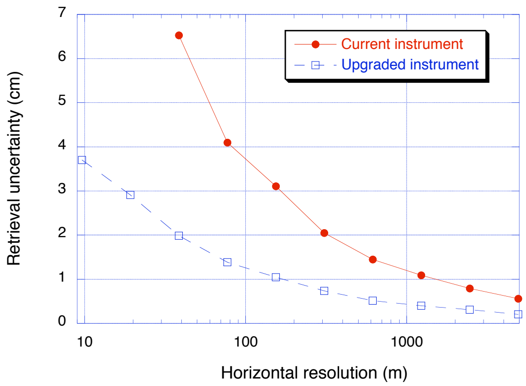

Figure 5. Resolution-dependence of snow thickness retrieval uncertainties caused by observational noise. True snow thickness is 40 cm. The upper curve is for the THOR4ice instrument (with only minor upgrades); the lower curve is for an upgraded instrument with faster photon counting and automated iris mechanism.

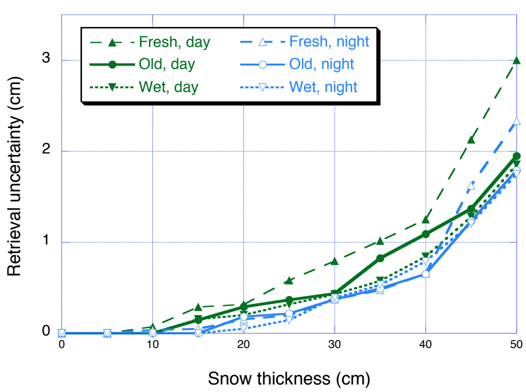

Figure 6. Typical daytime and nighttime retrieval uncertainties due to observational noise for the three snow types described in Section 2. Horizontal resolution is assumed to be 1.2 km. Daytime and nighttime retrievals are for 30° solar and lunar elevations, respectively, and assume full moon. Full and empty symbols indicate daytime and nighttime observations, respectively. Dashed, solid, and dotted lines are for fresh, old, and wet snow types respectively. For wet snow we plotted the results for 0.7 g cm^{-3} snow density; uncertainties for 0.4 g cm^{-3} snow density are very similar.

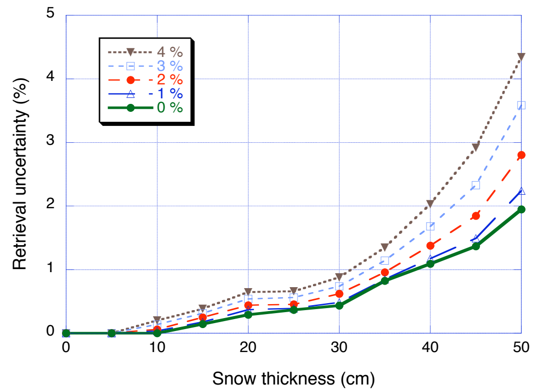

Figure 7. Retrieval uncertainties due to errors in relative calibration. The legend indicates the average calibration error for each curve. Each point is based on the average of 100 retrievals that used uniformly distributed random calibration errors with the indicated mean calibration error values. The figure shows the results of 1.2 km resolution daytime retrievals for old snow, and so the lowest curve is identical to a curve in Figures 4 and 6.

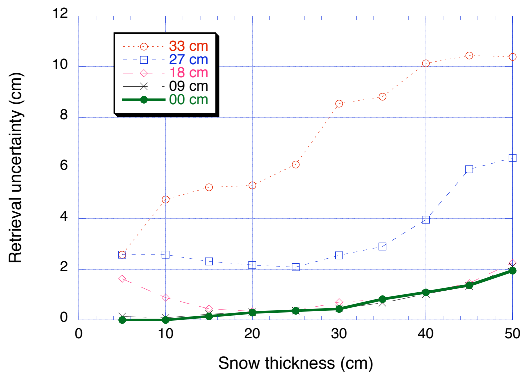

Figure 8. Snow thickness retrieval uncertainties caused by finite beam width. Each curve is for a different beam diameter, but all calculations assume 1.2 km-resolution daytime retrievals from 8 km altitude, over old snow. The curve for zero spread is identical to the lowest curve in Figure 7.

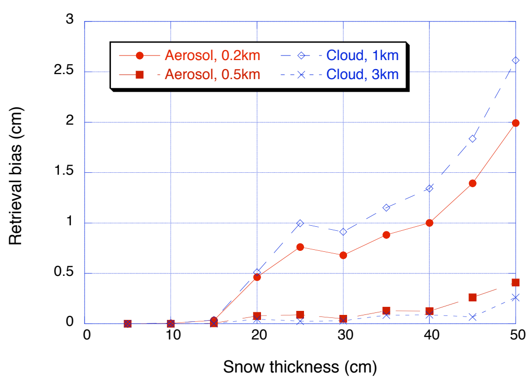

Figure 9. Biases that arise if retrievals don't consider scattering by clouds and atmospheric aerosol. All curves are for the "old" snow type and for a cloud/aerosol optical thickness of 0.2. As indicated in the legend, each curve is for a separate cloud or aerosol altitude,. Clouds cause larger errors because droplets tend to scatter more light into near-forward directions where they can influence our retrievals, whereas aerosol scatter more sideways, outside our fields-of-view.

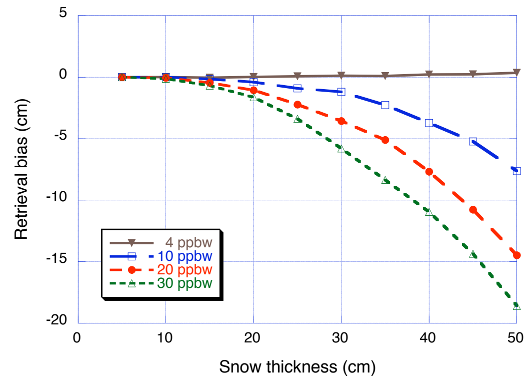

Figure 10. Retrieval biases caused by uncertainties in snow aerosol content. The retrievals assume 4 ppbw concentration for strongly absorbing aerosol. Each curve is for a different true aerosol content. The small bias arising even if the scene really has 4 ppbw aerosol is due to the random observational noise (assuming 1.2 km resolution) and calibration uncertainty (2%).

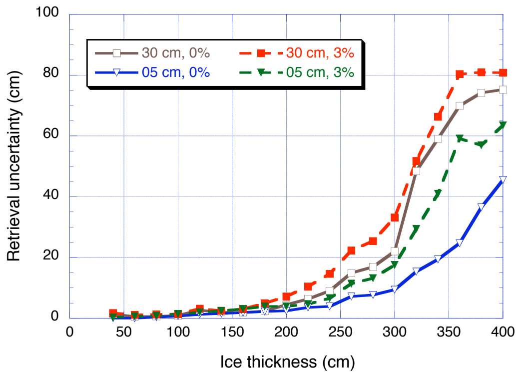

Figure 11. Uncertainty of nighttime sea ice thickness retrievals for various snow thicknesses indicated in the legend (assuming old snow). Only uncertainties due to observational noise and calibration errors are considered: two of the curves with full symbols are for accurate calibration, while the other two (with empty symbols) are for 3% mean calibration error.

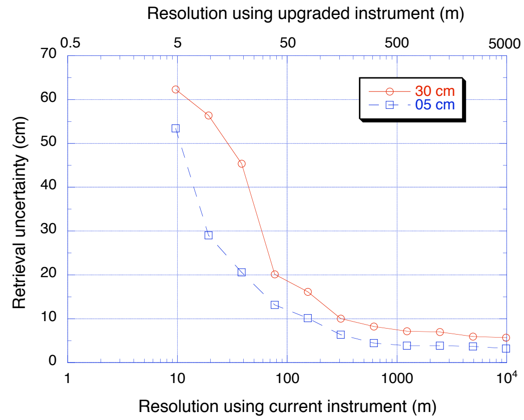

Figure 12. Resolution-dependence of sea ice thickness retrieval uncertainties caused by observational noise and 3% calibration uncertainty. The lower scale curve is for current THOR4ice instrument capabilities; the upper scale indicates the resolution that could be achieved by increasing the telescope diameter twofold (still fitting into the NASA P-3B or WB-57 aircraft). For resolutions higher than 77 m, the data system should be modified to average lidar returns over less than the current 0.5 s. The two curves are for 8 km-altitude nighttime observations of 2 m ice covered by 5 or 30 cm old snow, respectively.

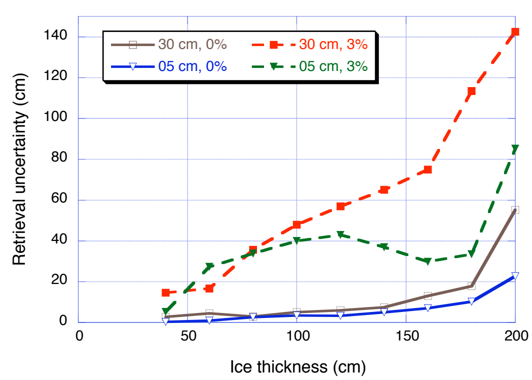

Figure 13. Same as Figure 11, but for daytime observations.